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Dependence of Bootstrap Current, Stability, and Transport on the Safety Factor Profile in DIII-D Steady-State Scenario Discharges

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Disclaimer

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This Work Tests the Dependence of the Bootstrap Current on Choice of Target Safety Factor (q) Profile

<u>Important for Achieving Steady-State Development Goals</u>

- Fully noninductive operation with a high bootstrap current fraction $f_{BS} \sim \beta_P \sim q\beta_N$
- Avoid local noninductive "overdrive" $J_{BS}+J_{AUX}>J_{TOTAL}$ incompatible with steady-state
- Achieve sufficient fusion gain $G \sim \beta_N H_{89}/q_{95}^2$ (G=0.3 for ITER Q=5 operation)
- Conventional approach has been to maximize q_{min} and β_N with q_{95} set by a trade-off with G

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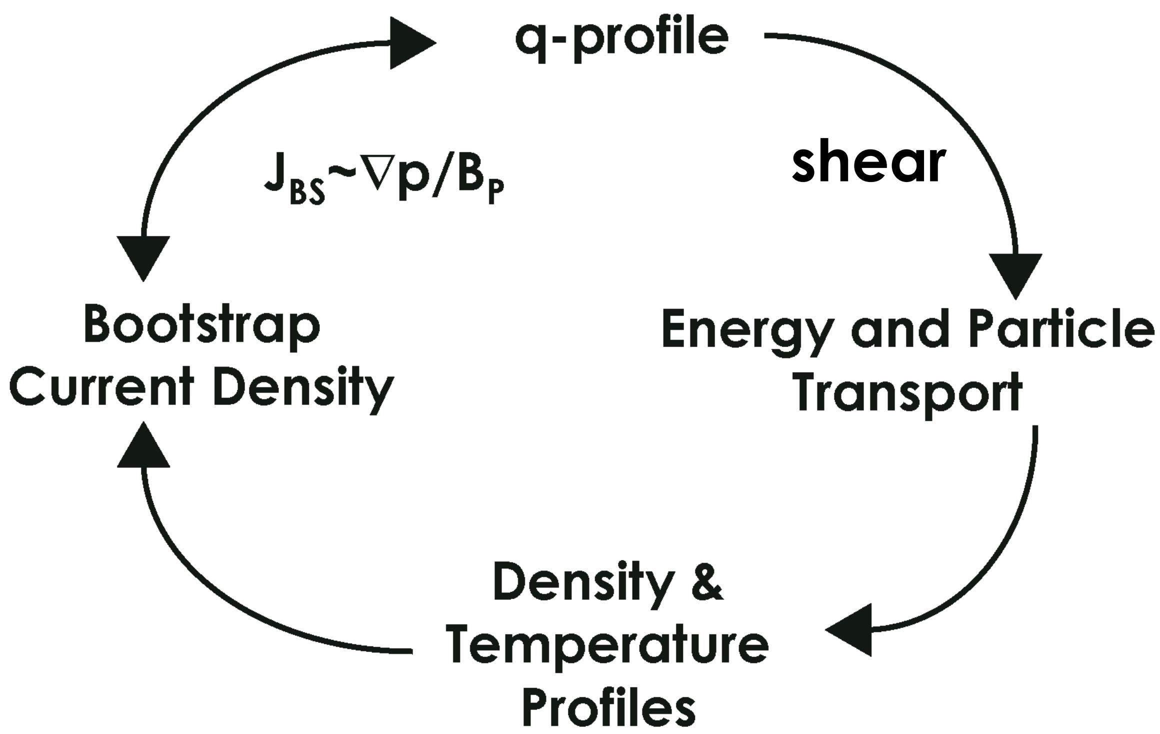
There is a Recursive Relationship Between Target q-Profile and J_{BS} at high f_{BS}



- Limits our ability to predict J_{BS}
- Experiment designed to vary q and measure resulting profiles

Experiment Produced Nine Different q-Profiles With $q_{min} \approx 1.1, 1.5, 2$ and $q_{95} \approx 4.5, 5.5, 6.5$

- q_{95} adjusted by I_P at fixed B_T
- First scan at fixed β_N=2.8 and second scan pushed β_N to maximum limited by stability or confinement
- Measured q, density and temperature profiles
- Calculated Bootstrap Current Density using '99 Sauter Model in ONETWO

$$\langle J_{BS} \rangle = \frac{F}{B_{T0}} \left[T_e \frac{dn_e}{d\psi} (L_{31}) + n_e \frac{dT_e}{d\psi} (L_{31} + L_{32}) + T_i \frac{dn_i}{d\psi} (L_{31}) + n_i \frac{dT_i}{d\psi} (L_{31} + \alpha L_{34}) \right]$$

- Compared measured quantities averaged over few hundred to ~1000 ms for better statistics

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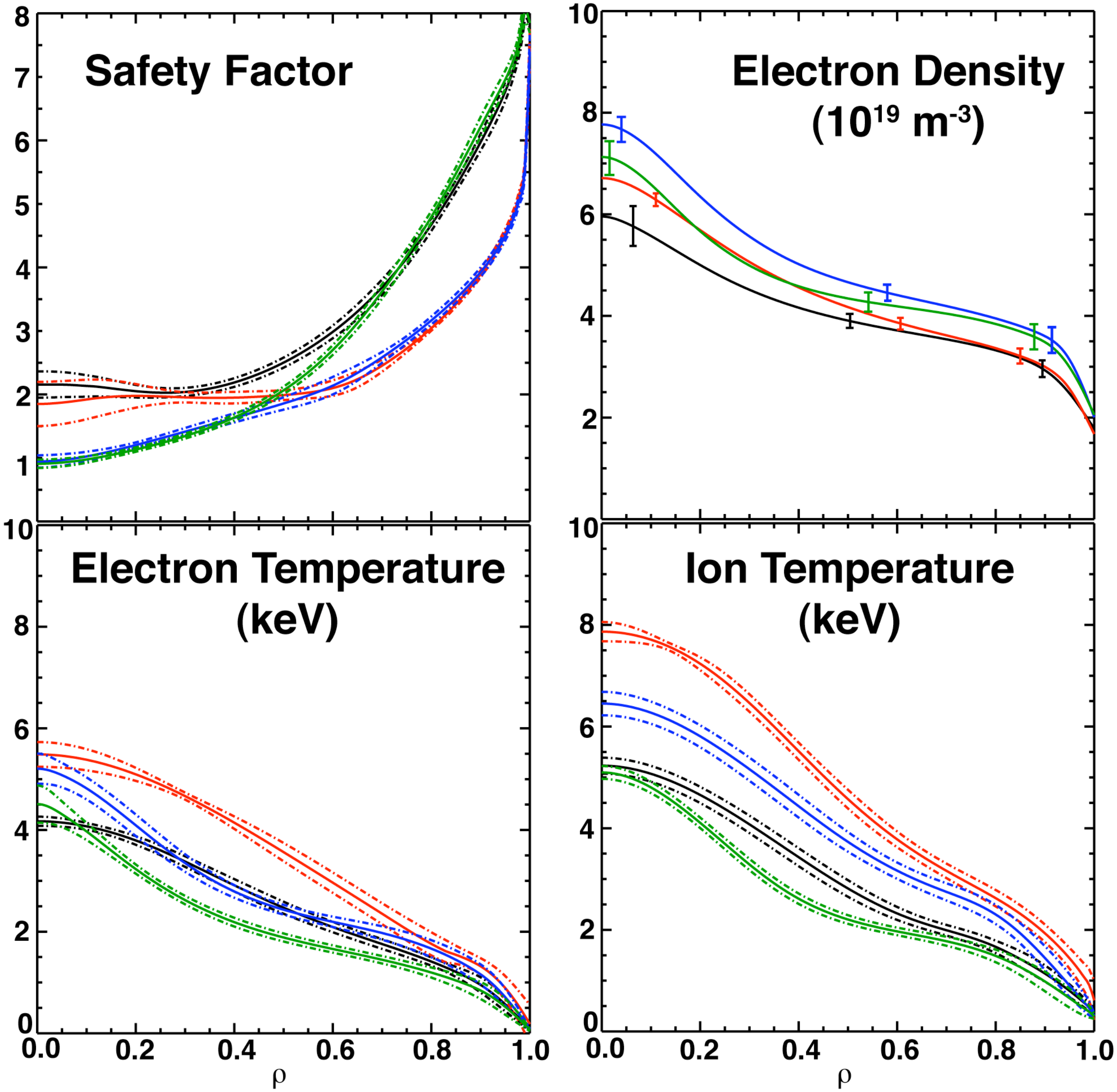
q-Profile Variation at β_N=2.8 Lead to Systematic Differences in Measured Density and Temperature

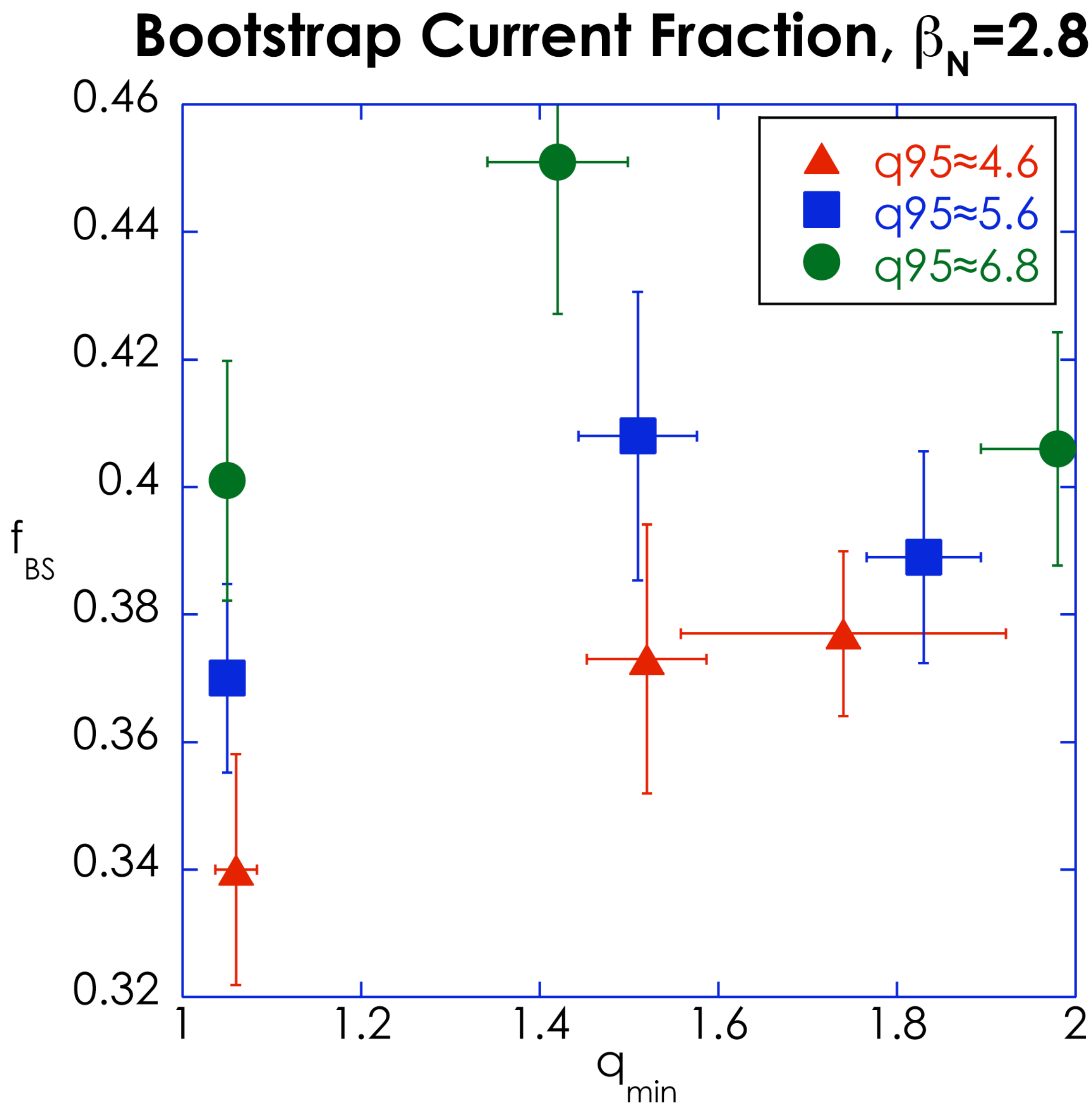
		q_{95}	
		4.5	6.5
q_{min}	2	136837	136835
	1.1	136854	136853

- At low q_{95}
  - n_e, T_e and T_i generally higher
- At low q_{min}
  - n_e higher and more peaked
  - T_e more peaked
  - T_i lower



At β_N=2.8, the Bootstrap Fraction Increases With q_{95} As Expected From f_{BS}~$q\beta_N$

- **Bootstrap Fraction leveled off or dropped with q_{min} above ~1.5**
- **This is contrary to expected $q\beta_N$ scaling**



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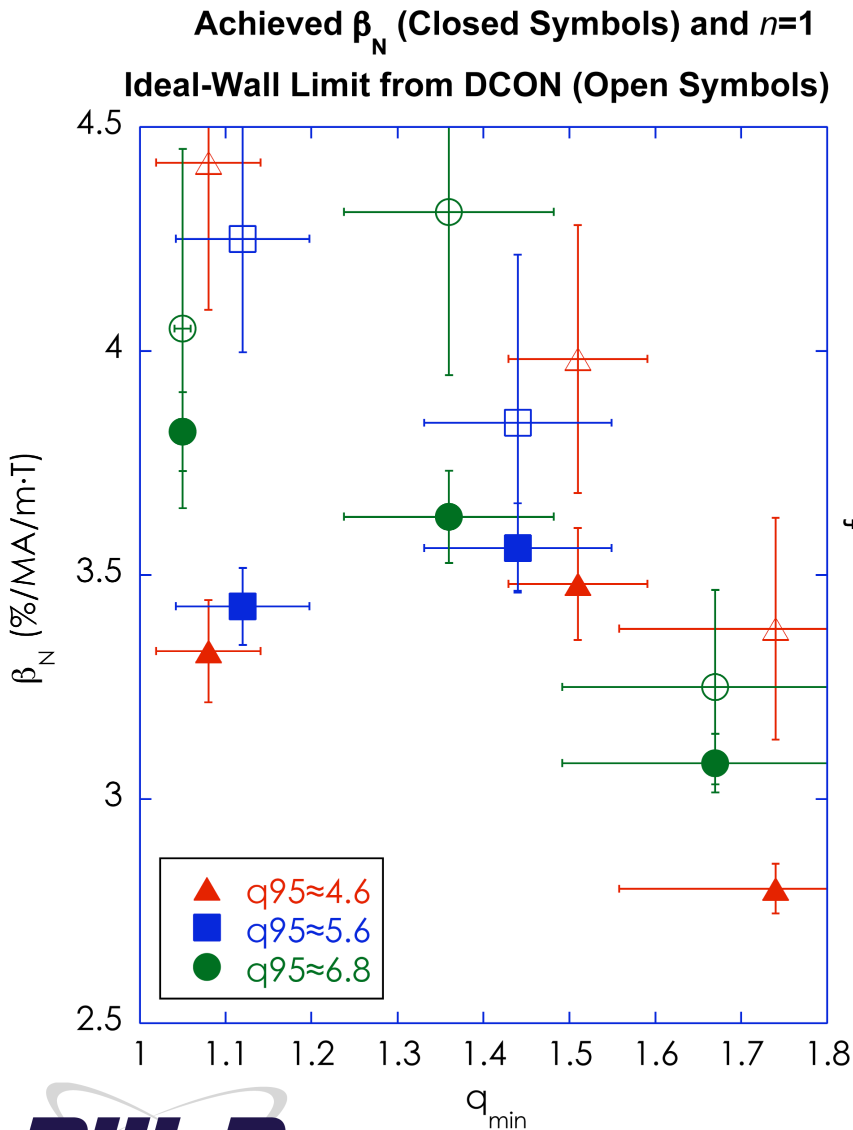
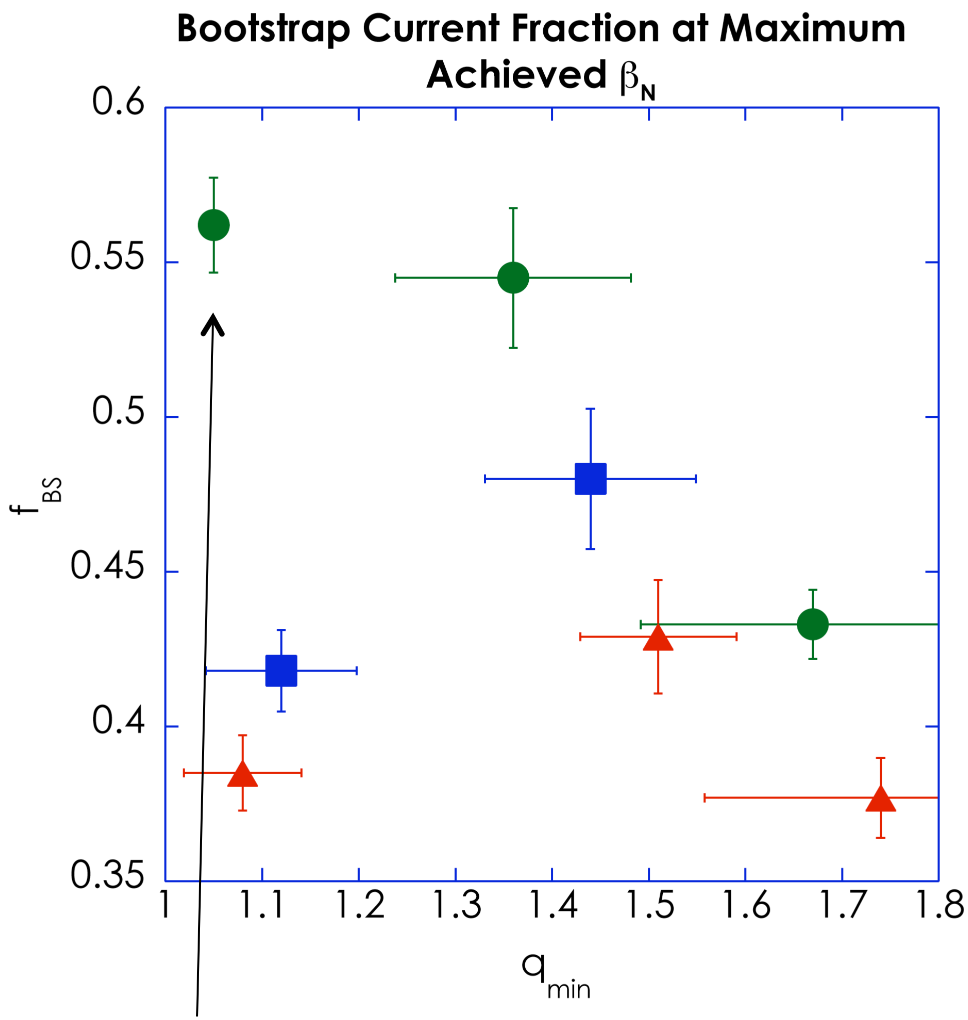
Increased Stability at Lower q_{min} Resulted in Highest Achieved β_N and f_{BS} Occurring at $q_{min} \approx 1.1$





Lowest q_{min}, $q_{95}\approx6.8$ discharge had ~10% higher H_{89} than all others

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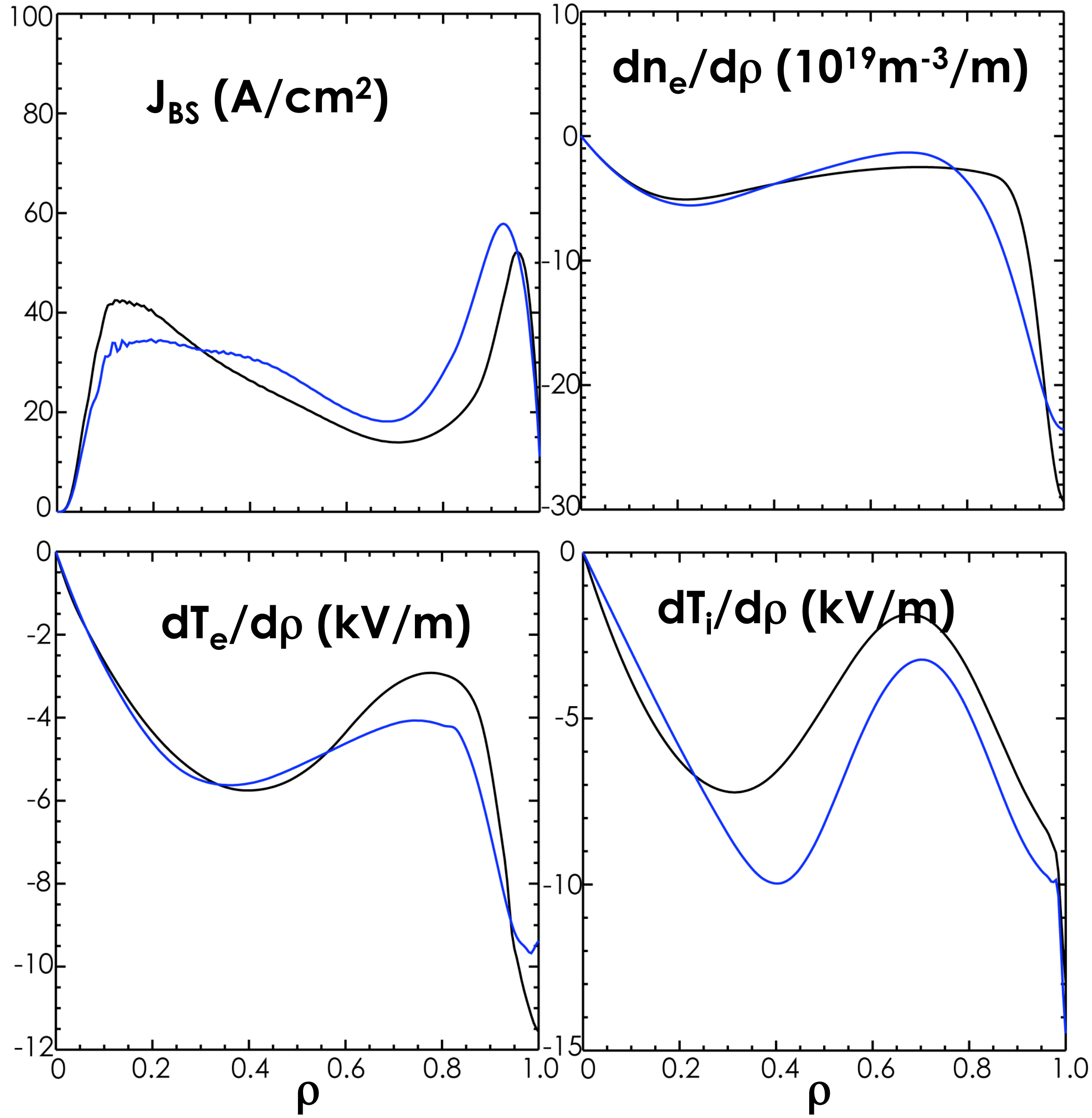
Increasing β_N Broadens J_{BS} By Increasing ∇T_e and ∇T_i at Larger Radius

- This example: q_{95}=5.6, q_{min}≈1.5
  β_N ≈ 2.8, 3.6
- Similar broadening with β_N for all q-profiles
- Broadening favorable for avoiding local noninductive current overdrive near ρ~0.2
- $dn_e/d\rho$ change with β_N not clearly systematic with q



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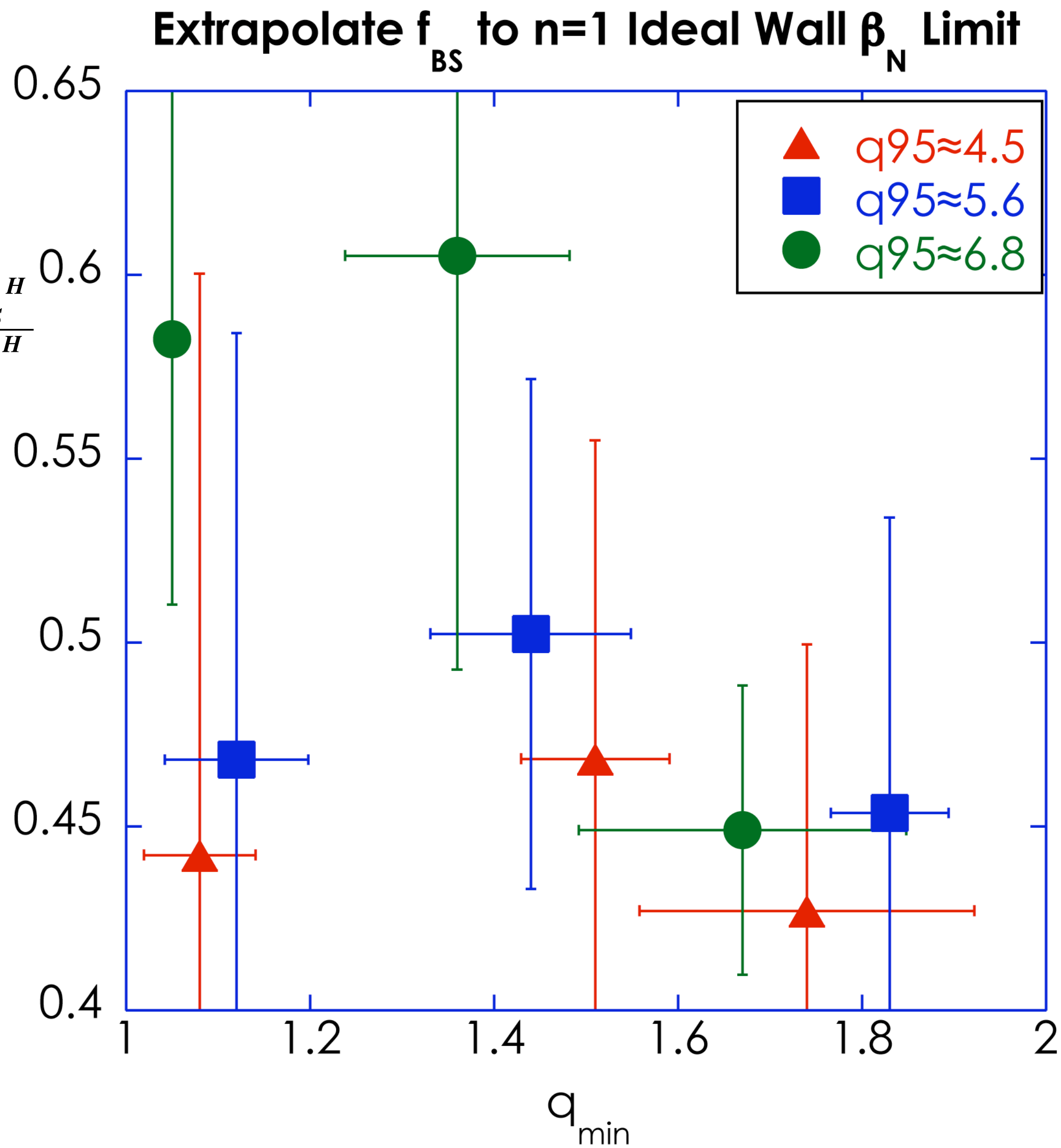
Extrapolating to the n=1 Ideal Wall β_N Limit Suggests f_{BS} Maximizes Near q_{min}≈1.5

- **Used measured f_{BS}/β_N to scale f_{BS} to ideal wall limit**

$$\frac{f_{BS}{}^{IW}}{\beta_N{}^{IW}} = \left(\frac{\frac{f_{BS}{}^{H}}{\beta_N{}^{H}} - \frac{f_{BS}{}^{L}}{\beta_N{}^{L}}}{\beta_N{}^{H} - \beta_N{}^{L}} \right) \left(\beta_N{}^{IW} - \beta_N{}^{H}\right) + \frac{f_{BS}{}^{H}}{\beta_N{}^{H}}$$

(L, H, IW refer to cases with β_N=2.8, maximum, calculated ideal wall)

- **Accounts for density and temperature profile scaling with β_N**



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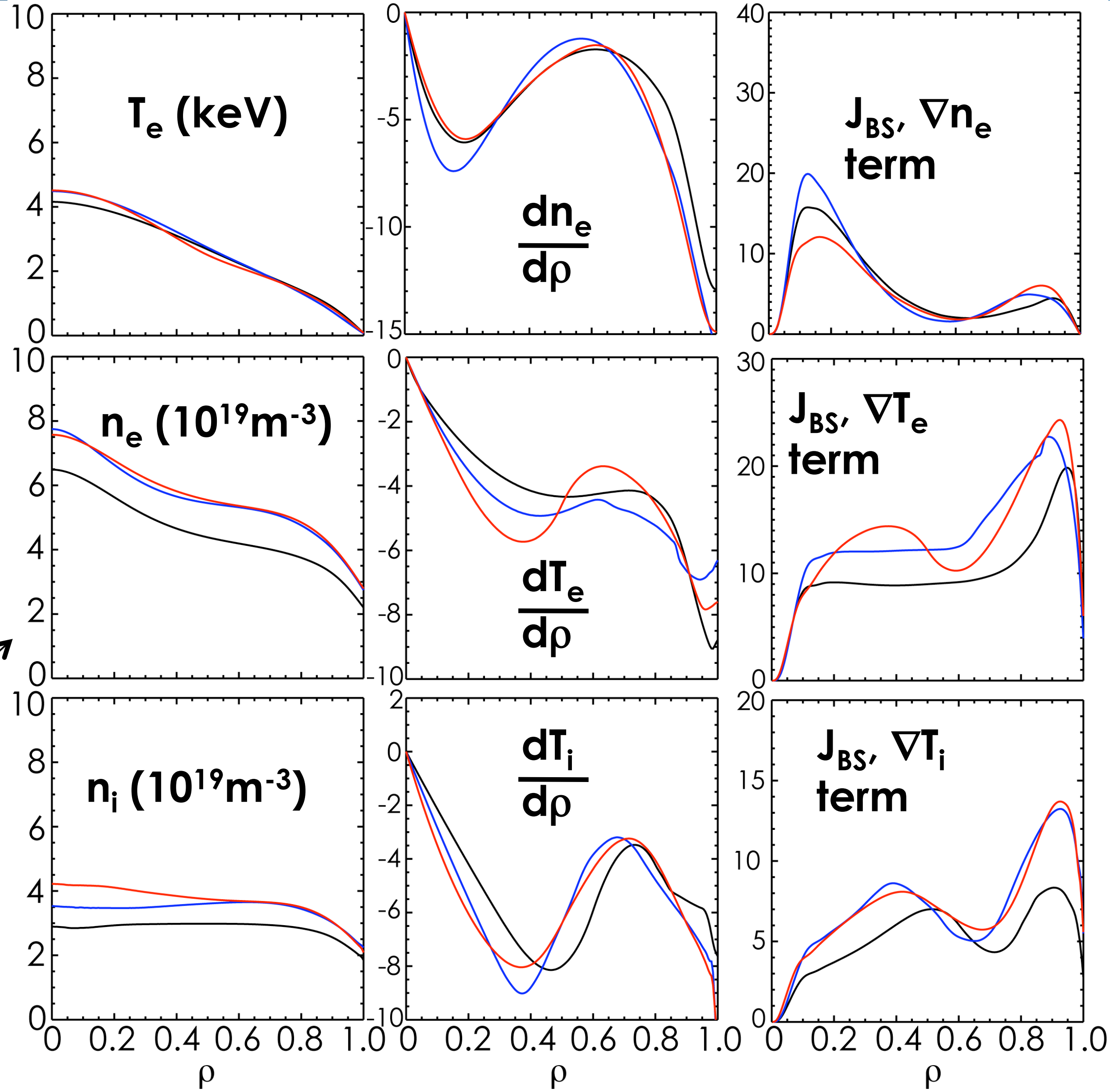
Lower f_{BS} at $q_{min} \approx 2$ Caused Mostly By Lower Density and Lower Temperature Gradients*

- q_{95}=6.8, scan of q_{min}≈2, 1.5, 1.1
- β_N pushed to maximum
- In each row, first two quantities are leading scale factors of bootstrap terms in 3rd column



*

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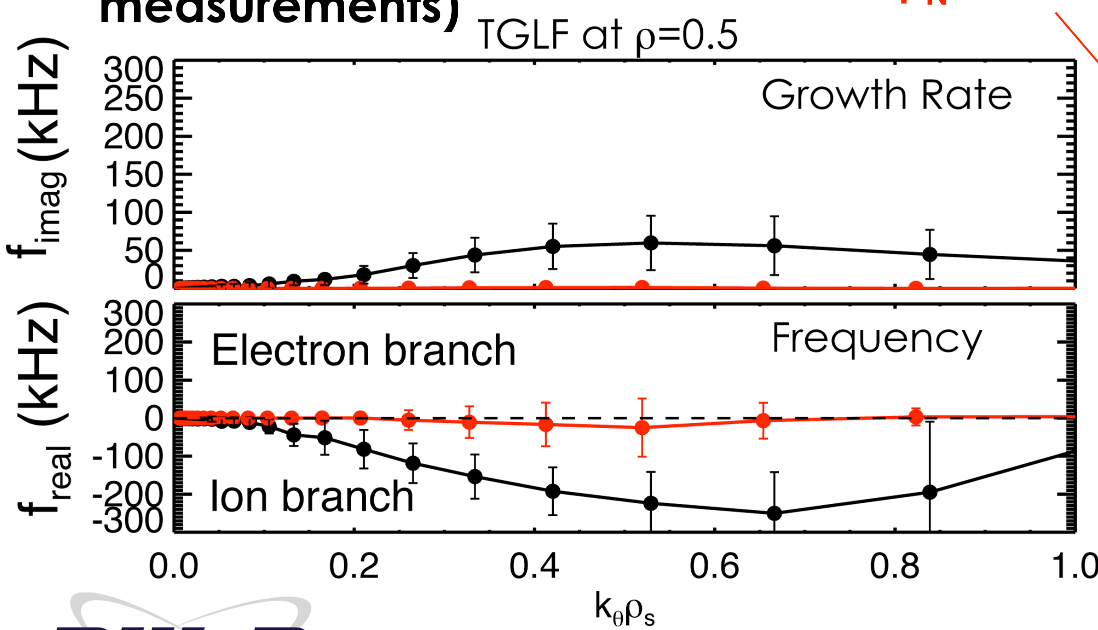
q_{min}≈2 Had Higher Measured Density Fluctuations and Calculated Growth Rates Than q_{min}≈1.1

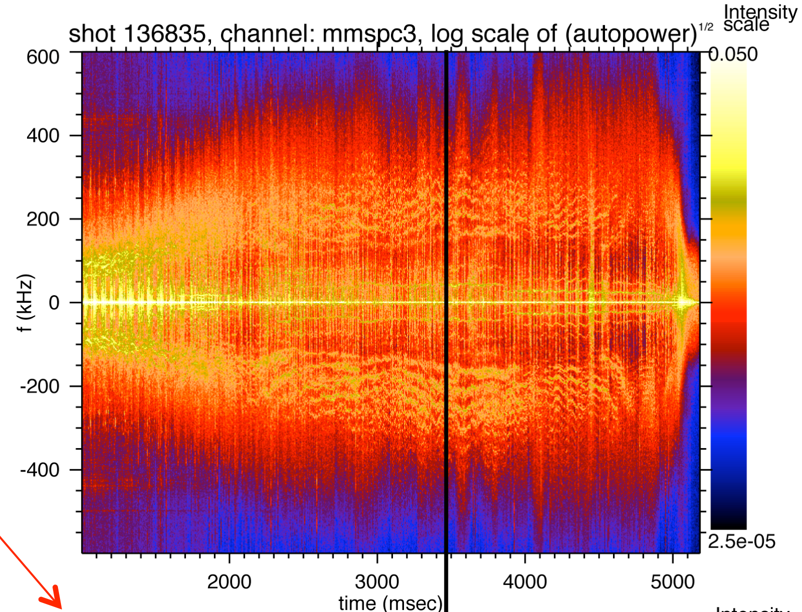
- k_θ<1 cm^{-1}FIR scattering measurement of ñ higher amplitude at q_{min}≈2

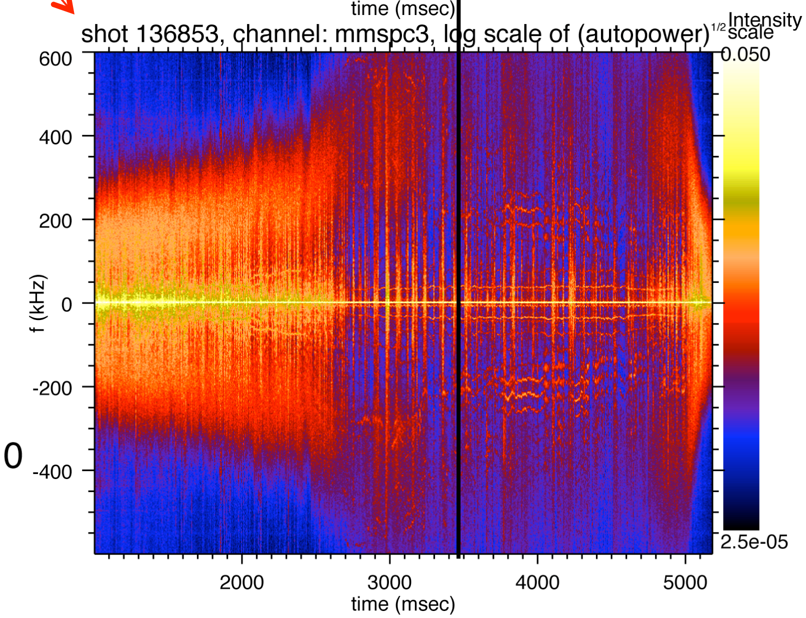
q_{min}≈2
q_{95}=6.8
β_N=2.8

- Linear TGLF runs show q_{min}≈1.1 was basically stable, q_{min}≈2 unstable to ITG type turbulence at mid-radius (consistent with measurements)

q_{min}≈1.1
q_{95}=6.8
β_N=2.8







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Summary and Conclusions

- In our scans of q_{min} and q_{95}, the bootstrap current fraction increased with q_{95} but did not continue to increase with q_{min} above about 1.5 as expected by $f_{BS} \sim q\beta_N$
- With existing control tools, $q_{min} \approx 1.5$ appears optimal for maximizing bootstrap current if the calculated ideal wall limit can be reached (only narrowly more so than $q_{min} \approx 1.1$)
- $q_{min} \approx 2$ discharges achieved lower β_N and calculated n=1 β_N limits, had increased transport, lower density, lower temperature gradients, and as a result did not produce as much bootstrap current
- Highest f_{BS} achieved at highest q_{95} (=6.8), but scan suggests lower q_{95} is required for more reactor relevant fusion gain $G \sim \beta_N H_{89} / q_{95}^2$
- New tools (off-axis NBI, more ECCD) may allow access to higher β_N limits and higher bootstrap fractions

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